

OPTICAL INTERFEROMETRY FOR THE EVALUATION OF MATERIAL AND STRUCTURAL CHARACTERISTICS

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ABSTRACT

Of interest in many engineering applications is the change in shape of a body or the change in strain distribution within a body when it is subjected to altered external conditions. To be of maximum use, methods for evaluating these conditions should not affect performance of the body; that is, they should be nondestructive. Optical interferometric techniques have been used extensively to determine the displacement of the surface of a body between two differing states. They are both nondestructive and offer a wide field of view. Depending upon the particular method that is chosen, displacement resolution can range from about 10^{-2} μm (100 Å) to 10^3 μm (1 mm). Various forms of image shearing (displacement) interferometry are capable of measuring the derivative of the surface displacement between two states and hence can give directly the strain distribution. Many of these methods can be performed in real-time. In this case, an image of an appropriate reference state is formed and then used to compare with other states generated by a change in external conditions. We have found interferometric methods valuable for a number of specialized studies. Residual strain induced by cycling to increasingly higher pressures within the plastic flow regime has been measured in experimental pressure vessels. This information is being used to determine the optimum welding method and parameters for high energy rate forged stainless steel. Sub-surface defects and material inhomogeneities frequently manifest themselves as an asymmetric or localized distortion of a body. We have used holography to search for localized deformation in fabricated components such as wound, fiber-epoxy pressure vessels. The elastic strain and thermal expansion of fabricated components have been measured using holography; this permits actual physical properties of the components to be compared with design or table values. These various applications of interferometry will be discussed in relation to practical problems and compared with other optical methods, in particular, speckle shearing interferometry.

Introduction

Optical methods for materials characterization are being used quite extensively; they are particularly well suited for applications requiring non-contact sensing or when gathering information simultaneously over a large area is necessary. Visible light can only give direct information about the region very near the surface (about 1 μm). This direct surface information is frequently not sufficient. There are, however, conditions such as subsurface defects whose presence can cause a surface to behave different from that of a perfect body when subjected to an external stress. The usefulness of this procedure of comparing a body in a stressed and unstressed state (or at two different stress levels) depends upon the displacement produced by a given external stress: if a measurable displacement can be obtained using stresses much less than actual load conditions, then such a test can be considered non-destructive. In any case, this is an active test more like acoustic emission than the truly passive examination procedures of radiography or ultrasonics.

Most engineering structures are designed such that under normal operating stresses, the resulting displacement ranges over distances large compared to the wavelength of light (about

0.5 μm). Hence even though external stresses must be used, they can normally be considered non-destructive. Moreover, various interferometric methods can give information about body performance under actual operating stress levels or in some cases can be used to determine the residual stress caused by a fatigue cycle.

In a typical measurement, the initial (relaxed or normal) state of the body is taken at the reference state. The body is then subjected to a deformation which establishes a new equilibrium surface. A variety of double exposure optical interferometric methods can be used to determine the difference between the initial and final surface.

Holography, the most sensitive of the interferometric methods, can be used to plot displacement contours separated by distances as small as one-hundredth the wavelength of light if the proper refinements are used. This means that surface deformations can be determined using an extremely small applied stress. If measurements at operating stress levels are desired, then it may be necessary to utilize some other interferometric method having reduced sensitivity to displacement. The remainder of this paper will discuss the use of holography with a comparison between holography and some other interferometric methods being given in the last section.

Holography

Figure 1 shows schematically how a hologram is produced³. Energy from a coherent light source (laser) is divided into two beams by a variable intensity beam splitter (BS). Each beam is focused onto a small aperture (diameter about 10 μm) to produce a good spherical wavefront over an angular spread of from 10 to 40 degrees (this so-called spatial filtering removes intensity variation from sources such as multiple reflections from optical surfaces, e.g. a beam splitter, and diffraction from dust on optical components). One of these beams illuminates the object which is often coated with a substance to make the surface a good diffuse scatterer. The other beam provides a phase coherent reference which is directed at the photographic plate where it adds vectorially with the light scattered from the object surface. The reference-to-scattered object beam intensity ratio is set to about 3:1 so that the scattered object beam varies the developed plate density about the reference level. This establishes a diffraction grating in the form of an interference pattern on the plate. When the developed plate is illuminated with a beam identical in form to the original reference beam (but usually brighter), light diffracted from this interference pattern reconstructs the original image which can then be photographed by a camera.

In order to view an object in its initial and final states, two holograms must be made and compared. This is most frequently done by exposing the first hologram, changing the external stress and then exposing the second hologram on the same photographic plate in exactly the same position. For the small displacements of interest here, the two images appear to be precisely superimposed with a series of dark bands on or near the object. These bands result from interference of light scattered from identical points on the two, slightly displaced, images. The separation between dark bands represents about a half wavelength displacement between corresponding surface points. The exact relationship between true surface displacement and distance between dark bands depends upon the holographic setup and is derived later.

A quantitative interpretation is not as simple as might first appear. An external stress which deforms a body may also cause it to rotate or translate. These later effects must be removed from the former in order to deduce characteristics of the body material.

Interpretation of the interference pattern that results from double exposure holography has been the subject of many interesting papers^{4,5}. It is readily demonstrated that the interference pattern is determined by the component of displacement bisecting the illumination and viewing directions. For other than parallel light illumination, the illumination direction will vary over the body surface. Thus, a general description of the pattern of dark bands must include, among other things, specifying the

illumination and viewing directions. This makes it difficult to establish "standard" patterns.

Many problems are alleviated if one makes the viewing and illumination directions coincident⁶. A very practical setup that accomplishes this is shown in Fig. 2. The 1:1 beam splitter achieves the desired viewing and illumination but it does increase the exposure time by a factor of four for any given incident power level. Although having these directions coincident is not essential for quantitative holography, it greatly simplifies the interpretation. For instance, any symmetry in the object being viewed can show up in the interference pattern. For convenience, the analysis that follows is for the special case of coincident viewing and illumination directions.

Let $\vec{M}(\vec{r})$ be the displacement of a point on the surface of the object that occurred between two exposures and let $(\hat{i}, \hat{j}, \hat{k})$ be unit vectors in (x, y, z) coordinate system. Take \hat{k} to be the illumination direction. The optical path difference caused by this displacement (assumed to be in air) is then $2 \vec{M}(\vec{r}) \cdot \hat{k}$. Destructive interference (dark bands) will occur whenever the displacement between two points r_1 and r_2 satisfies the condition

$$2 [\vec{M}(\vec{r}_1) - \vec{M}(\vec{r}_2)] \cdot \hat{k} = n\lambda \quad (1)$$

where n is an integer.

In general, the displacement $\vec{M}(\vec{r})$ will have contributions from rigid body rotation and translation as well as that due to the desired deformation of the body being studied. As a case in point, let us consider the pressurization of a uniform elastic spherical metal shell, a segment of which is shown in Fig. 3. Here one has

$$\vec{M}(\vec{r}) = (a\hat{i} + b\hat{j} + c\hat{k}) + (\vec{r} \times \vec{\omega}) + (\kappa P \vec{r}) \quad (2)$$

where the first term represents rigid body translation, the second rigid body rotation and the last uniform elastic expansion proportional to the internal pressure, P . Since all displacements are small, they add vectorially. The optical path difference is therefore

$$2 \vec{M}(\vec{r}) \cdot \hat{k} = c + \alpha y - \beta x + \kappa P z \quad (3)$$

where $\omega = (\alpha, \beta, \gamma)$. It is also useful to define a fringe density function

$$\vec{p} = \nabla (\vec{M}(\vec{r}) \cdot \hat{k}) \quad (4)$$

which, for the case being considered, becomes

$$\vec{p} = -\beta \hat{i} + \alpha \hat{j} + \kappa P \hat{k} \quad (5)$$

Already, many general statements can be made. Note that rigid body translation merely causes a constant phase shift over the entire body thereby neither changing the number of fringes nor the fringe density. Rotation produces a constant fringe density independent of the shape of the body. The only contribution to a fringe spacing that varies over the body is, in this case, the elastic deformation of the spherical shell upon pressurization.

For a sphere of radius a , $z = (a^2 - x^2 - y^2)^{1/2}$. Consequently, constant phase contours (that is, contours of constant z) are circles centered on the image of the sphere. If being viewed in the equatorial plane of the sphere, the fringes appear as concentric circles. In general, the fringes are projections of these circles on the plane normal to the viewing direction. Figure 4 is a photograph of the reconstructed image obtained from a double exposure hologram by changing the internal pressure of a spherical vessel. Rotation is almost completely absent. The circles are not quite concentric because the viewing direction (in this case, the orientation of the camera) is slightly above the equatorial plane of the sphere.

A small rotation gives interference patterns very similar to those of an anisotropic body with no rotation. There is not enough information in one view to determine anisotropic elastic properties. Two views of the same region taken simultaneously provide additional information (equations). Such a procedure has been used in evaluating welds in high energy rate forged (HERF) stainless steel pressure vessels. Figure 5 shows the reconstructed image viewing the weld region directly and by a mirror. The plastic strain distribution in the vicinity of the weld is shown in Fig. 6. The weld is rigid compared to the material in the heat affected zone (HAZ) on either side.

The thermal expansion coefficient of bodies of simple geometry can be measured quite easily using holography. Typically, a 5°C temperature change between exposures is required. Coincident illumination and viewing makes data reduction much simpler but is certainly not necessary. Figure 7 shows the interference pattern obtained using the setup in Fig. 1 with about 25 degrees between illumination with parallel light and the viewing direction. This right circular cylinder was heated about 2°C between exposures. In the coincident geometry and with no rotation, one would obtain a series of vertical lines getting more closely spaced toward the edge of the cylinder. In Fig. 7 there is no indication of such an idealized pattern; this is due in part to the experimental geometry and in part to rigid body rotation.

Holography is also very useful for a qualitative examination of objects. Figure 8 shows the results of double exposure holography used to examine fiber epoxy pressure vessels. Such bodies are highly non-uniform and quite anisotropic and hence yield a complex interference pattern. Good vessels, however, tend to have patterns that repeat so this can be

used as a qualitative means of examining the entire surface of a body which is otherwise very difficult to inspect.

Summary

Optical methods have been used quite extensively in NDT for the qualitative inspection of components. The purpose of this paper is to point out that interferometry can be used for the quantitative determination of some useful engineering parameters of fabricated components. For example, we have measured the residual stress introduced by cycling a pressure vessel to its operating pressure and the variation of the thermal expansion coefficient over the surface of an isotropic body.

The examples discussed are applications of holography because that represents the majority of our experience to date. Other interferometric methods are being developed both here and elsewhere. Of particular interest are the various forms of speckle shearing interferometers.⁹ These have two main advantages: they are less sensitive to rigid body rotation than holography and the contour interval can be set independent of the wavelength. Because two images are produced, one slightly displaced from the other, that is, sheared, the output is directly the derivative of the displacement, namely the strain. Hence, this is truly a wide field strain gauge. Disadvantages include effective loss of displacement information (although this can be obtained other ways) and a slightly more complex reconstruction process.

Our developments are motivated by the need to determine materials characteristics in finished parts and to be able to perform NDT inspections with the operator remote from the part (such as for tests in a high pressure or other hazardous environment). These are rather specialized applications but, in many cases, after proper development effort, the inspection procedures can be executed by good quality technical personnel. Quantitative as well as qualitative optical NDT methods should be considered as just some of the many tools in the NDT repertoire.

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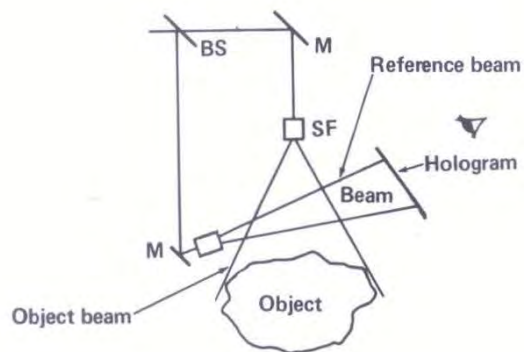


Figure 1. Typical minimum setup required to produce a hologram; components and their function are described in the test.

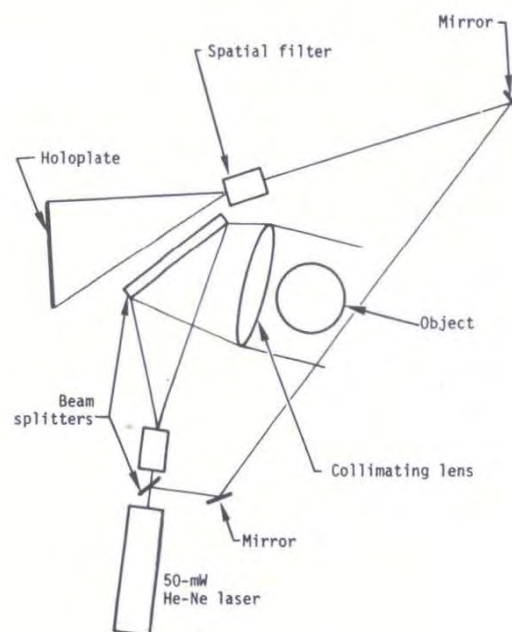


Figure 2. A holographic setup utilizing coincident illumination and viewing directions.

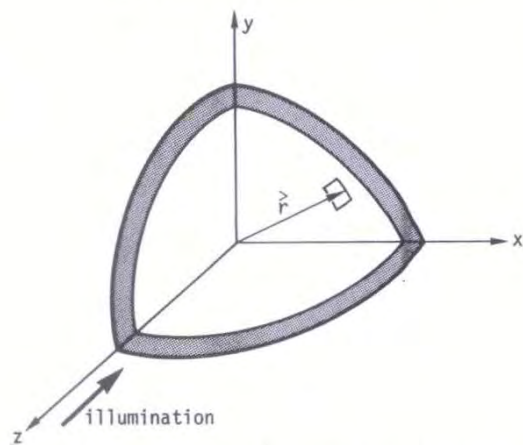


Figure 3. Coordinate system used to calculate the fringe pattern for coincident illumination and viewing of a pressurized spherical shell.

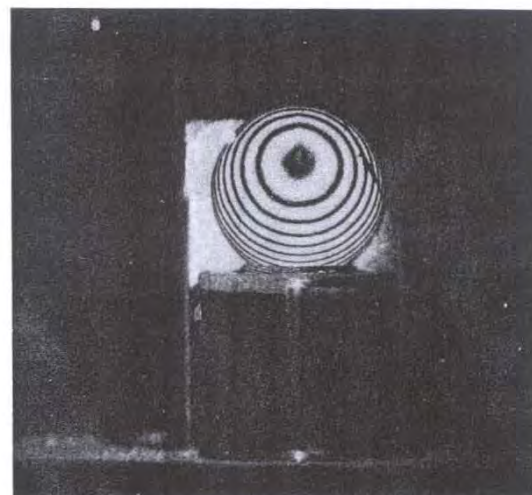
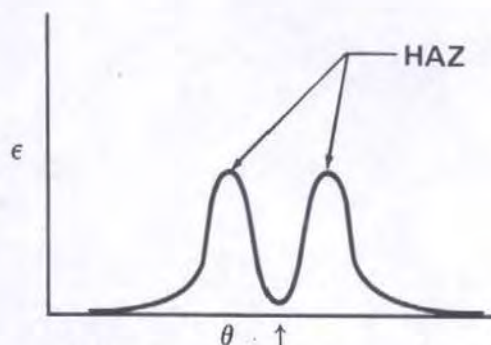


Figure 4. Reconstructed image of the interference pattern for the pressurization of a spherical vessel.



Figure 5. The reconstructed image of a two-view hologram of a portion of a diametrical weld in a stainless steel pressure vessel.



Plastic strain in the vicinity of a weld.

Figure 6. Plastic strain distribution in the vicinity of a diametrical weld after pressurization significantly above proof pressure; plastic flow has taken place in the heat affected zone (HAZ).



Figure 7. The interference pattern obtained by changing the temperature of a cylindrical specimen by about 20°C, but in this case coincident illumination and viewing was not used. Note that there is essentially no evidence of cylindrical geometry.

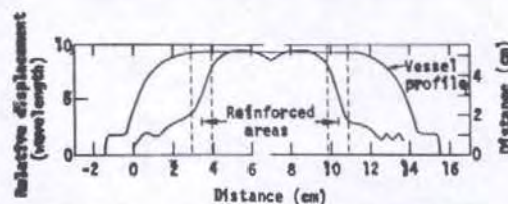


Figure 8. Reconstructed image of the interference pattern resulting from pressurization of a fiber-epoxy pressure vessel.